



# **Workshop on Nanotechnology Infrastructure Final Report May 7, 2012**

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**Arlington, VA**

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**Nanotechnology Infrastructure Workshop**

**April 3-4, 2012**

**Hilton Arlington Hotel**

**Arlington, VA.**

**Co-Chairs:**

**James Yardley, Columbia University**

**Jeff Welser, Nanoelectronics Research Initiative of Semiconductor Research Corporation**

## 1. Executive Summary

Nanotechnology is generating entirely new scientific and technological opportunities that offer revolutionary solutions to major problems of society including energy, health, environment, climate, and economic development. The robust advancement of research and development for Nanotechnology within the United States will require the support of a state-of-the-art physical infrastructure that is widely accessible. For the past decade, the National Nanotechnology Infrastructure Network (NNIN) has served as a major and enabling factor for extremely-successful development. As the NNIN moves toward the end of its designated program term and as nanotechnology progresses toward the new Nanoscale systems, an important issue is: what capabilities should NSF generate and nurture in order to provide the important and critical needs for continued development of Nanotechnology? Accordingly NSF has supported a workshop of recognized national experts to evaluate the needs of, and appropriate future investments in, a national infrastructure for nanotechnology. The workshop was held in Arlington, VA on April 3-4, 2012 with 22 participants representing a wide range of stakeholders. The participants examined the opportunities provided by a nanotechnology infrastructure as well as the needs of the scientific and technological communities for realization of these opportunities. On this basis, the workshop participants urge the formation of a new infrastructure network. As envisioned, the infrastructure network will build on the fundamental fabrication tools that have been developed by the electronics industry, including lithographic patterning. However the infrastructure will be distinguished from the current NNIN by incorporating the following major elements, to offer a much broadened scope and user-base:

- (1) Emphasis on utilization of the network nature of the program to provide value to the stakeholders far greater than individual components.
- (2) A user-base that is much broadened beyond electronics and electronic device fabrication to include less traditional communities such as environmental sciences, geosciences, and biosciences.
- (3) Availability of new cutting edge fabrication capability to users who require it.
- (4) Capabilities to create complex and three dimensional Nanoscale systems through heterogeneous integration.
- (5) Capabilities to build Nanoscale systems across multiple dimensional scales through hierarchical design and fabrication.
- (6) Major extension of capabilities for fabrication in soft matter including potentially biological interfaces.
- (7) New generations of modeling and simulation along with the use of new design tools to maximize overall understanding and fabrication efficiency.
- (8) Facilities capable of supporting the translation of discovery into prototypical elements suitable for evaluation of manufacturability and proof of business concept.
- (9) Partnerships with industry, government, and other groups to provide specialized capabilities within the network when warranted. The network will also include linkages with other networks and federal infrastructure investments, such as facilities at NIST and DOE.
- (10) Coherent unified program of education and outreach built upon the unique nature of the network and funded at a level commensurate with the goals and directions of the program.
- (11) Commitment to support and champion environmental responsibility, health, and safety (EHS) by providing direct capabilities (characterization and fabrication/synthesis) as well as establishment of the benchmark for EHS within a university environment.
- (12) Incorporation of understanding of societal and ethical implications (SEI) of nanotechnology.

This infrastructure network will cultivate support through strong partnerships and collaborations with other federal agencies with active interests in Nanoscale Science and Engineering as well as with industrial and governmental research facilities.

## **2. The Nanotechnology Revolution, National Nanotechnology Initiative, and National Infrastructure.**

In recognition of the potential for Nanoscale Science and Engineering to bring about a series of revolutions in science and technology – ranging from electronics to biological and medical sciences to totally new materials and beyond – the United States created the National Nanotechnology Initiative (NNI) in 2001. The NNI strategic plan has identified specific stages in this revolution beginning with passive systems, moving through active nanostructures toward *systems of nanosystems* and ultimately *molecular nanosystems*. One of several national programs in support of the NNI has been the National Nanotechnology Infrastructure Network (NNIN). This program has served as a major and enabling factor for the extremely successful transition from passive to active nanostructure stages for the past decade. Over the next 10-12 years, the NNI roadmap anticipates transition from active nanostructures toward systems of nanosystems. Thus today an important issue for NSF to examine is: what capabilities should NSF generate and nurture in order to provide the important and critical needs for this transition?

It is clear that robust nanotechnology R&D and technical advancement will require the support of a state-of-the-art physical infrastructure that is geographically-distributed and easily accessible. The specialized capability, equipment, and structures needed for nanoscience R&D are prohibitively expensive for small enterprises and educational institutions. Sustained and predictable access to a broad range of state-of-the-art instrumentation and facilities for synthesis, processing, fabrication, characterization, modeling, and analysis of nanomaterials and nanosystems, including bio-nanosystems, is critically-needed to achieve this objective. In most cases, no single researcher or even single institution can justify funding the acquisition, maintenance, and support for all necessary tools, and therefore user-facilities that provide access to researchers from multiple sectors, including academia and industry, serve a critical role. Such facilities have the ability to co-locate a broad suite of necessary nanotechnology tools, to maintain these tools at the leading edge, and to provide staff with expertise to ensure the most productive use of the tools. In addition, they provide an outstanding setting for hands-on training of nanotechnology students and researchers.

The National Nanotechnology Infrastructure Network (NNIN) will reach its ten year authorized award life at the end of FY 2013. For these reasons, NSF has authorized a workshop of recognized national experts to evaluate the needs of, and appropriate future investments in, the national infrastructure for nanotechnology.

## **3. The Workshop**

The workshop was held on April 3-4, 2012 at the Hilton Arlington Hotel, in Arlington, VA. James Yardley (NSEC Director, Columbia University) and Jeff Welser (Director, Nanoelectronics Research Initiative of Semiconductor Research Corporation) served as co-chairs. The chairs recruited an extremely diverse set of 22 workshop participants who are nationally recognized experts in nanotechnology and in translating nanotechnology into new businesses with expertise including electronics, optics, biological sciences, biophysics, environmental science, geological sciences, materials science, social sciences, earth science, and computational science. See Appendix I for a list of participants and Appendix 2 for the agenda. The primary objectives of the workshop were:

(1) Identify the needs for major university-based user facilities that can most effectively stimulate discovery and technological innovation in Nanoscale Science and Engineering across a broad range of opportunity areas, including materials and physical sciences; nanoscale electronics, magnetics, photonics, and mechanics; biological, health, and medical sciences; environmental sciences and geosciences.

(2) Identify the most important opportunities provided by emerging new capabilities that user facilities can drive forward as major developments in Nanoscale Science and Engineering for the betterment of humankind.

(3) Develop and articulate a vision for a new-generation National Nanotechnology Infrastructure Network that will afford the research and technical development communities a set of user facilities and capabilities which can bring the identified opportunities to fruition in support of the needs for scientific, technological, and educational advancement.

(4) Identify the opportunities within the nanotechnology infrastructure user-facility context for supporting education and outreach activities and study of the societal and ethical implications of nanotechnology, including issues of environment, health, safety, and economic development.

#### **4. A New-Generation Nanotechnology Infrastructure Network: NG-NI. Needs and Opportunities.**

The availability of a nanotechnology infrastructure at a national level is critically important to bring the unique opportunities presented through nanoscale science and engineering. The information technology (IT) revolution and the growth of our IT-based economy have been driven by the economics of ever-smaller, thus faster, more power-efficient and less expensive electronic devices and components. The world-wide micro- and nanoelectronics industry is thus a leading front for innovation in nanotechnology. Continued vitality of the industry depends not just on continuously shrinking the known and established devices. It depends on repeatedly implementing entirely new materials, structures and devices. Fabrication technologies developed for nanoelectronics are being applied to new materials and emerging device areas. As one example, new concepts for nano-optical materials including meta-materials and photonic bandgap structures promise to support continuation of the optics revolution beyond basic fiber-optical communications to far-reaching systems utilizing extremely high speed information flow and wireless capabilities.

The development of fabrication capabilities within the electronics industry offers major opportunities to influence change in many additional fields, touching virtually every aspect of society. In the arena of biology and medical sciences, interfacing nanoscale components and devices with living tissue will drive the development of new medical devices, diagnostics, and treatment concepts. In the geosciences, nanoscale science and technology is bringing new materials and sensing techniques to understand geological processes at the most fundamental level. Nanotechnology has already revolutionized many aspects of environmental science, offering potential for understanding the toxicology of nano-materials (both natural and artificial) and for understanding and controlling the fate of chemicals and materials in the environment. Fundamental understanding of structure on a Nanoscale and the ability to fabricate new materials with zero defects over large areas will enable new high strength materials as well as nano-mechanical structures with myriad new functionalities for applications in smart buildings and other elements of the “smart world.” Increasingly, nanoscale structures and structuring for soft materials can create new materials with optical and mechanical properties that can serve many aspects of society. Thus it is clear that many needs of society can be supported and indeed enabled through the

availability of an infrastructure that allows researchers to make or fabricate Nanoscale objects and systems.

To enable these diverse system applications, an excellent infrastructure network is vital to the national research and development community, providing access to capabilities that would be otherwise out of reach. This community includes university researchers but it also includes start-up companies and small companies who are increasingly taking on the mission of developing innovation in the United States. Furthermore, this infrastructure can significantly assist the movement of new research-based concepts into prototype evaluation and on to manufacturable technology. This critical need to the future of the nation can be significantly assisted through availability of suitable infrastructure resources.

## **5. Vision for New Generation Nanotechnology Infrastructure: The NG-NI.**

The workshop participants urge that NSF create the “New Generation Nanotechnology Infrastructure” (or NG-NI). We envision a *network* of university-based open-access user facilities designed to provide researchers and emerging technology-based business with ready access to the cutting-edge capabilities for fabricating nanoscale components and systems needed to advance science and technology. The facilities offer equipment, trained operators and support for a broad user-base including university researchers, small businesses, startup businesses and other groups. The network structure provides for geographical diversity while assuring the most efficient use of resources that are expensive to maintain and operate. This network structure also assures that cutting-edge technology is available when needed. It strongly promotes interdisciplinary cooperation and collaboration and supports development of disruptive technologies. Finally, the network structure supports vertical integration in capability as needed to advance new technical concepts. The envisioned NG-NI is much more than a continuation of the existing NNIN; rather, the NG-NI expands this very productive program, creating a new program with a commission that is both broader and deeper and which will serve a much-expanded user-base.

The equipment and materials base for the NG-NI is built upon the incredible capabilities provided through the evolution of silicon semiconductor technology, but moves beyond this to provide capability for cutting edge fabrication, for fabrication in non-conventional materials, and for creation of nanoscale technologies in soft materials including polymeric materials and biological systems. The network supports small businesses and startups in development, evaluation, and determination of manufacturability for technology-driven business concepts. The network will develop an experienced workforce to support broadly the needs of business, government, and society at large. The network will support, develop, and promote societal responsibility and a broad sweep of educational programs. The user-interface will offer easy approach and usage, addressing a diverse and extensively broadened base of users, covering a wide range of projects and communities. It will provide knowledgeable staff to accommodate and train users, especially those with non-traditional experiences or backgrounds. These university-based network facilities and capabilities are augmented through vital and active partnerships with industry, national and federal laboratories, and other external groups, actively integrated into the overall operation of the network.

## **6. Key Capabilities Provided by NG-NI through its Own or Partner Facilities:**

### **6.1. Fabrication of Nanoscale Materials through Advanced Processing Techniques Driven by State of the Art Lithographic Processes.**

Lithography is the keystone, the core capability, of any infrastructure dedicated to the advancement of nanotechnology. Why? Because building any structure with interoperating parts, from the pistons and gears of a power train to the transistors and wires of an integrated circuit, requires that parts be highly reproducible. Lithographic tools are thus the machine tools of our era. As the precision of these tools has improved, the minimum reproducible feature size of engineered structures has been reduced and the complexity and capabilities of engineered structures has expanded. Although the state-of-the-art is driven by the economics of the world-wide microelectronics industry, the applications of lithographically defined micro- and nanostructures are rapidly expanding into other sectors of the economy. Newer lithographic processes, like elastomeric stamping and dip-pen lithography are better suited to "soft" materials and will increasingly find applications in biology and medicine, large-area and flexible electronics, and other emerging industries. Lithographic processes and systems are being developed to provide the templates for chemical processes (directed self-assembly) to produce structure on a molecular scale. Experimental scanning probe systems can fabricate some useful structures with literally atomic precision. Thus lithography will remain the key capability of any national infrastructure for nanotechnology. It is essential that this capability be refreshed on a regular basis and expanded to include the new techniques best suited to an expanding universe of applications. Although lithography is the linchpin, many other tools for deposition and etching are needed. The NG-NI relies heavily on capabilities and facilities that make these incredible tools available to a wide range of users, enabling entirely new applications. The expanding set of capabilities and facilities included in this vision are outlined below.

*a. Fabrication of Modern Electronic, Mechanical, Optical, and Electro-Mechanical Components.* A key value of NNIN has been to democratize access to the base tools and processes needed for general semiconductor fabrication. While this started with tools for silicon device processing, it has expanded to include tools for other materials (e.g. III-V, magnetic materials, etc.) and structures (e.g. MEMs/NEMs), and most recently tools suited to soft materials and biological applications. The necessary capabilities include sub-micron photolithography; e-beam writing for mask making and direct writing of nm scale patterns; a variety of deposition and etching tools capable of processing semiconductors, dielectrics and metals – in sufficient number and with proper protocols to allow a wide range of material processing without cross-contamination; and characterization capabilities for process monitoring. Co-location of the primary elements assures rapid and effective turnaround for increasingly-complex structures and devices. This core capability not only forms the backbone of many opportunities that will be of interest to start-up companies, but also is critical for educating students in the basic processing of nanoelectronics. And since no single university can afford all possible tools in this area, maintaining them within a network allows the most efficient use of funds and wide access across the country.

*b. Fabrication of Cutting-Edge Electronic, Mechanical, and Optical Structures.* The semiconductor industry continues to develop new cutting-edge capabilities in lithography and corresponding processing. These capabilities exist primarily within the leading fabrication and development laboratories for industry. The NG-NI will provide critical leading-edge capabilities through specialized facilities. For example high quality laboratory-based electron-beam lithographic tools can be used to create devices for research purposes. In addition through negotiated partnerships with semiconductor development laboratories, equipment manufacturers, and specialized development facilities world-wide the NG-NI will be able to provide access to these capabilities where critically needed.

*c. Non-Conventional Lithographic Patterning and Processing.* Although the semiconductor industry employs primarily optical lithography for mass production of high-end electronic devices, there are many other lithography tools that can fabricate nanoscale objects and devices for specialized or novel

purposes. Electron-beam lithography has become the workhorse for nanoscale electronic device fabrication and therefore is a critical tool. Nano-imprint lithography, originally developed as an alternative patterning technique for semiconductor fabrication, has found increased usage in a wide variety of fields including micro and nano-fluidics, magnetic storage, optical structures, sensors and diagnostics, and biological applications. Dip Pen lithography is an alternative means for fabricating nanoscale objects over modest areas, providing direct deposition and manipulation of nanoscale materials. Scanning probe techniques can also be used to directly write and read nanoscale patterns. Recent advances have demonstrated massively parallel patterning using two-dimensional arrays of tips. A number of embossing and nano-printing tools are now available for large scale nanofabrication. The NG-NI provides a set of such tools, carefully chosen to complement and augment the basic fabrication capabilities of the network. At the same time the network will provide the expertise to utilize these facilities in the most effective way.

*d. Fabrication Facility for Soft Matter.* The fabrication of nanostructures using polymeric soft materials as well as biological molecules is critical for a number of emerging applications - especially in the biological and medical sciences. Such materials will provide not simply flexible substrates for conformal compliance and improved interface with biological systems, but will also provide optimized “soft” surface structures and chemistry and stretchable substrates. The NG-NI will provide some of these capabilities, including at least one facility that can offer a broad range of soft matter fabrication processes under a single roof with experienced staff to assist in adapting the capabilities to the needs of a wide variety of users. Example capabilities include dip pen lithography, nano-imprint lithography, nano- and micro- scale embossing tools, and Nanoscale printing capabilities.

*e. Nanoscale Fabrication of Unconventional Materials.* Many important components today are being fabricated with unconventional materials. For example the semiconductor industry has developed a myriad of materials and materials processes for integrated circuits at the nanoscale such as  $\text{HfO}_2$ ,  $\text{Al}_2\text{O}_3$ , TaN, Ru, and TiN. The emergence of new materials like graphene and integration of these films with metals and dielectrics currently being investigated for future electronic applications, flat panel displays, supercapacitors, sensors, flexible electronics, and many more is also another key capability. There is also a need to understand and develop materials having multiferroic properties and topological insulators that take advantage of interface properties. Inclusion of these capabilities is an essential part of the NG-NI and will require specialized facilities.

*f. Nanoscale Fabrication Based on Self and Directed Assembly.* The NG-NI will need facilities to allow for the use of self-assembly and directed self-assembly for the creation of large area 2D and 3D nanostructures. Advances in block copolymer synthesis as well as colloidal assembly have been increasingly been utilized in semiconductor fabrication, magnetic storage, optical and biological applications. Facilities are needed that provide the availability of materials, processes and fabrication of nanostructures especially in the realm of these soft materials.

*g. Fabrication and Synthesis of Nanoscale Materials.* The New-Generation Nanotechnology Infrastructure will enable the creation of specific nano-scaled materials and objects. However, this need goes beyond fabrication of structures and includes direct fabrication or synthesis of nanoscale materials. This includes nanoscale particles which are becoming increasingly important for biology, medical science, environmental science and related important emerging applications of nanotechnology. It also includes fabrication of ultrathin films and coatings as well as membranes and filters with specified pore size, shape, and chemistry. Some of these capabilities reside within the broader range of general fabrication tools and capabilities, but others require alternative capabilities or tools. In addition, specific

expertise to define the optimal way to generate these objects and materials is critical. In some cases partnerships with National Laboratories or other facilities may prove to be effective for providing the tooling and equipment for these capabilities.

*h. Fabrication Capability Providing "Clustered" Tools.* Increasingly, control of the interfaces between layers in a nanostructured material or device is critical for the functional characteristics of the material. Thus there is significant need for fabrication capability wherein multiple processing steps (especially deposition and surface characterization) can be carried out within controlled environment or atmosphere. The NG-NI includes specialized capability wherein chambers for various material depositions (semis, metals, dielectrics) and characterization are grouped so that it is possible to transfer between them without exposing the interfaces to ambient.

## 6.2. Heterogeneous Integration: The Assembly of Three Dimensional and Complex Systems.

The integration of fundamentally different material classes such as inorganic, organic and biological systems will provide opportunity for technological understanding and development. Fabrication and characterization techniques that allow the integration of heterogeneous materials and the study of these integrated materials and their interfaces will allow the development of integrated systems to address new applications. There is a need for fabrication infrastructure that allows, for examples, the marriage of biological material (cells, tissue) and fabricated substrates such as patterned molecular or organic templates to probe cell biochemistry and mechanics, or rigid and flexible electronic platforms to address cells and tissue, and nano- and micro-channels. Examples in energy technologies include combinations of organic and inorganic materials or different nanostructured materials for photovoltaics, etc. and their integration on non-traditional substrates, such as flexible plastics and glasses. Note that this also drives a need for more low-temperature processing and solution-based processing capabilities, as well as the ability to integrate all of these materials and structures. Thus the NG-NI will provide specific capabilities and tools to enable such heterogeneous integration including the following.

*a. Heterogeneous Integration: Integrating Nanoscale Subassemblies into 3D Systems.* Large-area fabrication techniques combining dissimilar materials and devices offer an opportunity to translate devices and components into systems. This can be accomplished through interconnecting building-blocks, providing different function, to operate cooperatively at a system level. Emerging industry capabilities in advanced assembly and 3D chip stacking, including flip-chip bonding and "through-Si vias", allow integration of dissimilar materials to generate new system architectures. For example, heterogeneous integration of III-V semiconductor materials with silicon-based technologies enables systems that incorporate optical sources and detectors or extremely high speed electronics interfaced through more conventional silicon technologies. Similarly the emergence of graphene and other truly novel materials that provide totally new circuit elements will be extremely important in the next decade. All of these developments and trends represent critical needs for the NG-NI if it is to truly provide new opportunities for creating complex systems based on nanotechnology. Beyond assembly of 2D-processed nanoscale devices and materials, 3D integration ultimately also encompasses the creation of new functionality through 3D self-assembly and 3D patterning of heterogeneous materials. This is expected to be especially true in soft materials, nanoparticles for catalysis and chemical applications, and biological applications. To this end, NG-NI will support new deposition, lithographic, and characterization tools that support exploration in this direction.

*b. Integration of Nanoscale Components across Multiple Dimensional Scales.* Important advances in nanoscience and nanotechnology will be based upon the ability to understand and control the



properties of complex materials across a range of length scales. For example, nanoscale objects or domains with tailored properties will need to be interconnected. Many properties including quantum confinement, diffusion lengths, separation of charge or of chemical reagents will need some form of hierarchical design for spatial control. Consequently, there is a need for fabrication methods capable of integrating local and long-range structure and properties. These capabilities can derive in part from the paradigms developed in the semiconductor industry to translate for example transistor devices across many centimeters of distance through a series of circuit boards or “interposers”. For these reasons, capabilities for creation and assembly of suitable interposers are extremely important for advancement of components into systems. Furthermore, integration of Nanoscale devices within or on flexible substrates and soft materials will generate new opportunities and applications such as flexible or stretchable electronics, smart sensors, distributed sensors, “smart skins” and many more. Introducing these capabilities into the NG-NI will broaden the potential applications that can be researched by students and prototyped by start-up companies. Partnerships coupled with appropriate modeling and design tools can significantly strengthen these capabilities.

*c. Heterogeneous Integration for Biological Systems.* Constructing interfaces between biological media and “man-made” devices is a key driver for new developments in the biological and medical sciences. New materials interfaces, three-dimensional scaffolds, and integration with measurement circuitry provide opportunity for chronically and minimal-invasively probing of biophysical properties of biological systems in more representative models of the *in-vivo* environment. Especially, at the systems level, by interfacing nano-materials to electronics, we introduce the capabilities for chronic measurement and actuation of basic biological processes at the organismal scale. All of these issues are currently limited by interfaces between the device and the biological system, where nanotechnology will have an impact. The ability to co-integrate heterogeneous materials with electronics on multiple distance scales provides key enabling technology relevant to the evolution of fundamental biological and medical science.

### 6.3. Design, Simulation, and Modeling Tools.

The NG-NI must take full advantage of the coupling of modeling and simulation with fabrication for rapid and effective advancement of nanotechnology. This coupling is even more critical as we move toward systems-level technology. As the NG-NI increases focus on 3D structures and heterogeneous systems the complexity and scale of computation needed for the required simulations will challenge conventional hardware. Equally challenging will be provision for user-friendly interface between researchers from many disciplines with the complex fabrications required to generate nanoscale systems. Close cooperation between arms of NSF, DOE, NIST, and other agencies can help ensure that future massively parallel computers will be available to address these issues. The NG-NI facilities will provide suitable expertise to assist the user community in application of these advanced simulation technologies toward the advancement of their experimental programs, as well as utilizing the NSF’s Nanoscale Computational Network (NCN – aka “the Hub”) for additional simulation capability.

### 6.4. Advanced Characterization Tools.

State of the art characterization tools are indispensable for determining composition, morphology, structure, as well as electronic, optical and chemical properties of nanoscale materials. They are necessary for ensuring the efficacy of fabrication processes; for obtaining information about device operation and failure; and for revealing nanoscale aspects of the natural world. For example, atomic resolution imaging using aberration-corrected electron microscopy has delivered remarkable capability for nanomaterial characterization. Moreover, in addition to continuing to push for higher spatial

resolution, higher temporal resolution is becoming increasingly important, to enable dynamic characterization of growth or fabrication processes [e.g. in situ monitoring of Atomic Layer Deposition (ALD) processes] as well as device operation (e.g. imaging the real-time flipping of a magnetic domain). Important capabilities for building next generation components and systems include:

*a. Characterization Tools Sensitive to Function.* Especially important tools for nanomaterial imaging and analysis are those that are sensitive to functional aspects of nanoscale objects (particularly local chemical or electrical properties) and that can track dynamic changes within the complex environments relevant to medical, engineering or environmental applications. Thus establishment of facilities offering complementary scanning probe measurements, using tips sensitive to multiple aspects of a system, will represent important capability.

*b. In-Situ Characterization.* There is a need for access to Nanoscale characterization instruments that are capable of operation *in situ*, to provide real time monitoring of fundamental characteristics. Examples might include the introduction of fluid cells for the TEM, combined with external electrochemical or mechanical controls. *In situ* characterization will enable or improve many fabrication processes that are currently not available or that have process control issues.

*c. Three-Dimensional Characterization.* The ability to work in three-dimensions will be invaluable for characterizing devices that combine nano-materials in order to achieve new properties or functionality, and for tracking the ways that nanoscale particles and devices interact with cells, tissues and other components of the natural world.

#### 6.5. Facilities for Translational Development of Nanoscale Components or Systems.

Commercialization of both federally funded research and entrepreneurial innovation based on nanoscale science and technology is critical for maintaining U.S. leadership in advanced manufacturing. This activity, in turn, provides a vitally-important source of high-wage employment to drive economic multiplier effects. To fully-realize this opportunity requires *translational research*: iterative prototype development toward market requirements, and development of scalable manufacturing processes. Failure to do the last step, in particular, makes it less likely that the manufacturing jobs and knowledge benefits of innovations will accrue in the U.S. A key mission of the NG-NI is to provide capabilities that can assist in *translational research*. For this reason, the NG-NI will include suitable capabilities for scale-up of technology that can be evaluated for overall efficacy and manufacturability. For example, these capabilities could include tools for creation of large scale nanopatterning either through batch processing or advanced roll-to-roll techniques as appropriate. Such specific scale-up capabilities should probably be implemented as needs emerge, but from its start, NG-NI should have a plan to support such capabilities.

#### 6.6. Facility Support for Understanding the Environmental and Health Aspects of Nanomaterials and Nanotechnologies.

The NG-NI will provide capabilities that support research needs on the environmental, health, and safety (EHS) aspects of nanomaterials and nanotechnologies. Capabilities required for EHS research include access to nanoscale materials and to characterization tools for physical-chemical properties of the materials as well as their impacts on reference organisms from the standpoint of toxicity and developmental endpoints. Because nanomaterials are often altered by their environment, characterization tools are needed for elucidation of nanomaterial transformations, such as protein

adsorption, oxidation, and aggregation in physiological and environmental systems. EHS activities within the NG-NI should also include the development and dissemination of protocols for the fabrication of nanomaterials and their characterization. In order to facilitate the understanding and responsible use of nanomaterials throughout the product lifecycle, the NG-NI will maintain a centralized database describing nanomaterial preparation and characterization protocols used by the NG-NI as well as characterization data produced by the network. These activities should be integrated into state-of-the-art practice in handling of nanomaterials and workplace safety within the NG-NI. These practices should also be made available to the overall nanoscience community with the goal of ensuring the safety of laboratory personnel. EHS information from the NG-NI should be disseminated as appropriate to educate the research community and the general public on EHS issues.

## **7. Key Operational Features and Attributes for NG-NI.**

### **7.1. Highly Networked Operational Structure Based on Unique University, Business, and Government Capabilities.**

The NG-NI is envisioned as a university-based collection of facilities and capabilities that are nodes of a closely integrated network providing service to the users. Ideally this network should provide for each user a single entry point into the full capabilities of the network. The network should provide well-maintained facilities, trained operators, and an interface that can help determine the optimal means for accomplishing the tasks desired. The network can provide basic capabilities at geographically-diverse locations coupled with more specialized capabilities that are available at fewer sites and utilized as necessary. The network structure assures maximum use of capabilities, while minimizing the costs of operation and maintenance. In addition, it can provide an extended base of experience and knowledge, crucial since these technologies are continuing to evolve and develop. The network allows for shared best practices. Also the network arrangement provides a natural means for vertical integration in which projects can evolve from simple component fabrication to complex devices to complex systems all within the same network. Societal responsibility and education are developed and promoted across the entire network, broadening the reach of these programs, while providing coordination and coherence in the programs and efforts. The network will provide a synergistic and coordinated educational program from kindergarten through graduate research and major outreach opportunities not only to the general public, but also to new potential users.

Through a set of strategic partnerships, the network will bring highly specialized capabilities to those programs that need them, providing a knowledge base to define which capabilities can best serve the user and providing pre-negotiated protocols for interaction of users with the partners. Thus key partnerships with industry, national laboratories, NIST, and international organizations can be leveraged to generate more complex integrated nanosystems. In addition these partnerships can be key elements in translating research into prototype systems for evaluation.

The NG-NI provides users access to the full range of network capabilities through a single point of contact requiring minimal bureaucracy. The NG-NI should provide help for identification of the most appropriate facilities and capabilities. It should also enable the interface between the users and partner facilities where needed. Moreover, NG-NI should focus on building a network that can go beyond individual device fabrication and enable system prototype integration. It will interface effectively with graduate students, postdocs, faculty members, research professionals, engineers at start-up companies, and other participants to prototype and evaluate new technologies.

### 7.2. Open Access that Respects Intellectual Property of All Users.

The NG-NI network provides open access that respects the intellectual property of all users. Thus all network facilities should provide a user agreement built upon a unified approach that is simple, easy to understand, and that assures open access as much as possible.

### 7.3. Geographically Distributed Capabilities.

Since the network is a national network, it should endeavor to provide a set of basic capabilities with general applicability centered at disparate geographic locations to maximize convenience to the anticipated user base. As much as possible, these basic centers should co-locate fabrication and characterization tools to allow for on-site fabrication and iteration of fabrication runs to optimize device or material parameters and properties. For specialized capabilities this may not be feasible, but the network should strive to assemble specialized capabilities into clusters of related processes and characterization tools, taking into consideration the locations of potential users.

### 7.4. Reasonable Costs for the User.

Ultimately, in order to develop a strong user base the NG-NI will need to assure that costs to the user are reasonable. The net cost to the user includes not only user fees or other direct costs of using the facility, but also costs for travel and for accommodation for graduate students, faculty, and other user staff.

### 7.5. Robust, Coherent, and Synergistic Outreach and Education Program.

An educated public and trained workforce is the foundation for sound science and technology policies, economic growth, and global prosperity. The NG-NI will develop, build, and sustain a robust coordinated, coherent, and synergistic program for stakeholder outreach and education with effective resource commitment, building substantially on the NG-NI programs and capabilities with committed participation by all participants. The education program should be a responsibility of the entire network, with resources focused to optimally leverage individual site capabilities. It is crucial that the education program be provided resources commensurate with the scale and ambitions of the program. There are two different aspects of the program.

*a. User Training.* Firstly, the network of NG-NI facilities will educate and train undergraduate and graduate students and other users in equipment purpose and operation, sample preparation and multi-disciplinary concepts that support various application and industry segments. This training not only assures safe and competent operations, but also assures that the program participants have a strong basic understanding for the science, engineering, and technology associated with the fabrication tools and processes. The skills developed by the students at these facilities will enable them to more easily transition to an industry-based environment. Where possible, new educational concepts including remote learning and training will be developed and incorporated, but these should in no way compromise the quality of the training.

*b. Broadly-Based Education and Outreach Program.* Secondly, NG-NI will engage in education and outreach activities appropriate to its vision and mission. As a provider of state of the art resources in a broad user network, education and outreach activities should be appropriate. An optimized agenda of educational and outreach activities designed to maximize the mission of the user network is a goal of

the NG-NI. Education and outreach should include informal education and public meetings. The network is an ideal place to encourage multidisciplinary research. Outreach in the context of the NG-NI should therefore include specific activities directed toward broadening the user base into non-traditional areas such as biology, geology, oceanics, and the like.

#### 7.6. Benchmark EHS Operational Characteristics Setting Standards within University Environments.

Any research facility will have operating hazards, but there are a number of specific issues for a Nanotechnology Infrastructure network which should have high priority. Firstly, Nanoscale fabrication involves the use of chemicals some of which may pose hazards of toxicity, fire, or explosion. The semiconductor industry has developed protocols for the safe use and handling of these materials. The NG-NI should incorporate these safe handling protocols into the university environment not only to assure safe operations for NG-NI, but also to set benchmarks for safety within the broader university research environments. Similarly the electronics industry has developed protocols for safe disposal of Nanoscale materials used or produced in nanofabrication and these should be followed rigorously. The incorporation of new non-traditional materials into the network capabilities will also require very careful assessment of the associated health and safety issues.

It is important to note in addition that extension of the network into soft matter and biologically relevant Nanoscale fabrication will require close attention to health and safety issues for materials and processes not covered by electronics industry standards. Furthermore as the NG-NI becomes involved in prototyping with concomitant increases in scale in order to evaluate and optimize systems needed for translational development, additional hazards may arise beyond those for small-scale research processes. For all of these reasons it is imperative that the NG-NI set a responsible example based on best available knowledge for health, safety and environment issues within its operations.

#### 7.7. Promoting Multifunctional and Multidisciplinary Teaming.

The NG-NI will encourage societal research and distribution of findings to stakeholders, taking advantage of the interdisciplinary user network nature as well as the overall research directions of the NG-NI. A dedicated effort to communicate critical and analytical information to stakeholders about the activities and accomplishments of the NG-NI and its impact on society at large is a goal of the NG-NI.

#### 7.8. Assessment of the Efficacy of Major Programs and Capabilities.

The goals and ambitions of this proposed network represent a substantial extension beyond those of the NNIN. It is critical that these goals and ambitions be carefully measured against specific objectives with clear and quantitative metrics. Such measurements will have credibility only if conducted by a truly independent agent. The evaluation process is critical to the overall operation of the program and should be actively established from the very inception of the network program.

### **8. Recommendations and Conclusions.**

Based on the needs and opportunities identified for the National Nanotechnology Initiative (NNI) and the concomitant benefits to society, workshop participants strongly urge NSF to establish a new-generation nanotechnology infrastructure network which will build upon the tremendous success of the NNIN, but which will provide a much broader and deeper commission. This network of university-based open-access user facilities will be designed to provide researchers and emerging technology-based

business with quick access to cutting edge capabilities for fabricating components and systems based on nanotechnology, for the advancement of science and technology, and for accelerating the transfer of basic research into new innovations that drive a high-tech manufacturing economy and broadly benefit society. The facilities will offer cutting edge equipment, trained operators and support to a broad user-base including university researchers, small businesses, startup businesses and other groups essential to the continued development of Nanoscale science and engineering. The New Generation Nanotechnology Infrastructure (NG-NI) will provide major capabilities for the creation and fabrication of new Nanoscale components, devices, materials, and systems that are currently unavailable to the research and development communities, as well as the facilities for integrating these into new nanosystems and prototypes. The new network will assure responsiveness and support for users, thus facilitating rapid exploration of new discovery and serving to drive innovation nationwide. Building upon its commission and capabilities, the network will provide comprehensive program for education not only for users, but also for business and the general public. It will reach out into new arenas for nanotechnology, assuring a highly diverse base of active participants well beyond the nanotechnology users of today.

While the NG-NI will be largely built upon a tool-base derived from developments within the electronics industry, the tool-base will be expanded to include facilities for fabrication in unconventional materials, such as soft matter and biologically compatible materials. It will include characterization tools to provide information for component evaluation, critical in building and evaluating nanoscale systems. It will include new patterning technologies. It will include capabilities for integration of heterogeneous materials into three dimensional and complex structures with the ability to integrate devices into systems on multiple dimensional scales. It will incorporate modern design and simulation tools closely coupled with fabrication tools and processes. It will include facilities and capabilities that will support the translational development of these components and systems into scales suitable for evaluation of manufacturing efficacy and market opportunity. Many of these capabilities will be provided through strategic partnerships designed to complement the facilities that are within the NG-NI, through industry, national laboratories and other national resources.

This New Generation Infrastructure Network will be clearly distinguished from the current NNIN by a number of new, enhanced, or expanded elements. These include the following:

- (1) Emphasis on utilization of the network nature of the program to provide value to the stakeholders far greater than individual components.
- (2) A user-base that is much broadened beyond electronics and electronic device fabrication to include less traditional communities such as environmental sciences, geosciences, and biosciences where interest in Nanoscale components and systems is rapidly increasing.
- (3) Availability of new cutting edge fabrication capability to users who require it.
- (4) Expansion of capabilities to create complex and three dimensional Nanoscale systems through heterogeneous integration.
- (5) Providing capabilities to build Nanoscale systems across multiple dimensional scales through hierarchical design and fabrication.
- (6) Major extension of capabilities for fabrication in soft matter including potentially biological interface.
- (7) Extensive use of new generations of modeling and simulation along with the use of new design tools to maximize overall understanding and fabrication efficiency.
- (8) Inclusion of facilities capable of supporting the translation of discovery into prototypical elements suitable for evaluation of manufacturability and proof of business concept.

- (9) Partnerships with industry, government, and other groups to provide specialized capabilities within the network when warranted. The network will also include linkages with other networks and federal infrastructure investments, such as facilities at NIST and DOE.
- (10) Coherent unified program of education and outreach built upon the unique nature of the network and funded at a level commensurate with the goals and directions of the program.
- (11) Commitment to support and champion health, safety, and environmental responsibility by providing direct capabilities (characterization and fabrication/synthesis) as well as establishment of the benchmark for EHS within a university environment.
- (12) Incorporation of understanding of societal and ethical implications (SEI) of nanotechnology.

The workshop participants recognize that the envisioned NG-NI may require a level of overall funding beyond the funding level of the existing NNIN. What we do not want is a network that is spread so thinly that it cannot deliver the overall vision. In addition, new or upgraded equipment may be required to upgrade existing facilities or to augment existing equipment to complete a suite of instruments needed to provide a unified capability. Thus it will be very important to provide capital funds in the startup phase for the new NG-NI program if at all possible. In addition, some trade-offs may be necessary between geographical diversity and breadth of capabilities in order to fund a viable program of this magnitude. We suggest that the NG-NI will need to be a national facility supported by collaborations and partnerships across the stakeholder federal agencies including not only NSF, but DOE (especially in the realm of characterization), NIST, and NIH so that its elements complement each other and work together seamlessly. Otherwise wasteful duplication may occur and critical capabilities will be missed.

## Appendix I. Workshop Participants.

|                   |  |
|-------------------|--|
| Bob Austin        | Princeton University, Physics  |
| David Berube      | North Carolina State University, College of Humanities and Social Sciences       |
| Ahmed Busnaina    | Northeastern Univ., Prof. and Director of Center for High-Rate Nanomanufacturing |
| Kenneth R. Carter | U Mass Amherst, Polymer Science and Engineering                                  |
| Luigi Colombo     | Texas Instruments, Nanoelectronics Research Initiative                           |
| Timothy Denison   | Medtronic, Fellow and Director of Neural Engineering                             |
| Ben Gilbert       | Lawrence Berkeley Laboratory, Earth Sciences Division                            |
| Cherie Kagan      | Univ. of Pennsylvania, School of Engineering, Chemistry                          |
| Thomas Koch       | University of Arizona, Dean, College of Optical Sciences                         |
| Laurie Locascio   | NIST, Chief of Biochemical Science Division                                      |
| Steve Lower       | Ohio State. Earth Sciences   |
| C. Bradley Moore  | University of California, Berkeley, Chemistry                                    |
| Deb Newberry      | Dakota County Technical College, Director of Nanoscience Technology Program      |
| Robert Opila      | Univ. of Delaware, Materials Science and Engineering                             |
| Robert D. Rung    | Oregon Nanoscience and Microtechnologies Institute                               |
| Mark Shephard     | Rensselaer Polytechnic Institute, Civil Engineering                              |
| Thomas Theis      | IBM, Yorktown Heights, NY  |
| James Turner      | SUNY, Binghamton, Small Scale Systems and Packaging Center                       |
| Roger van Zee     | NIST, Chemical Process Informatics   |
| Mark Wiesner      | Duke University, Civil and Environmental Engineering                             |
| Jeff Welser       | Director, Nanoelectronics Research Initiative of Semiconductor Research Corp.    |
| James Yardley     | Columbia University, Electrical Engineering, Director of Columbia NSEC           |



## **Appendix II. Agenda for Workshop.**

Agenda: Nanotechnology Infrastructure Workshop. April 3-4, 2012

### TUESDAY, APRIL 3

- 7:00 Continental Breakfast
- 8:00 Introductory Session  
Welcome and introduction of Chairs: Jim Yardley, and Jeff Welser (5 min.)  
Welcome: Tom Peterson, Assistant Director for Engineering for Engineering, NSF (10 min.)  
Welcome: Ian Robertson, Director of Materials Research, NSF (8 min.)  
Introductions: all participants and attendees (25 minutes)  
Welcome, Background of Nanotechnology Infrastructure and Workshop Objectives: Larry Goldberg, NSF (20 min.)  
Methodology and Agenda Summary: Yardley (10 minutes)
- 9:20 Breakout Session on Facility and Capability Needs for Driving Research and Development  
Group 1. Electronics, Photonics and Energy. Leader: *Ahmed Busnaina*  
Group 2. Health, Biology, Geosciences, and Environment. Leader: *Bob Austin*  
Group 3. Mechanics and Materials. Leader: *Cherie Kagan*
- 11:05 Break
- 11:15 Reports from Groups, Discussion, and Summary (Jim Yardley facilitator)
- 12:30 Working Lunch
- 1:15 Breakout Session on Opportunities and Capabilities  
Group 4. Fabrication including soft matter. Leader: *Roger van Zee*  
Group 5. Imaging and characterization (optical, scanned probe, others). Leader: *Thomas Koch*  
Group 6. Simulation, Modeling, Education, Society and Ethics. Leader: *Mark Shephard*.
- 3:00 Break
- 3:15 Report from Groups, Discussion, and Summary (Jeff Welser facilitator)
- 4:45 Setting the stage for the vision – facilitated discussion (Jim Yardley)
- 5:45 End of Day 1.
- 7:00 Working dinner at external restaurant for continued group discussions and idea generation.

### WEDNESDAY, APRIL 4.

- 7:30 Continental Breakfast
- 8:30 General session on Vision. Jim Yardley to facilitate
- 9:00 Breakout groups on Vision. Generate elements for a vision. Leaders: *Brad Moore* and *Bob Opila*
- 10:30 Break
- 10:45 Reports From Breakouts and Development of Consensus Vision. Jim Yardley, facilitator
- 11:45 Summary Discussion
- 12:15 Lunch, working
- 1:00 Adjourn